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REVIEW ARTICLE

Protecting the Community Through Child Vaccination

Evan J. Anderson,[1,2,a] Michael A. Daugherty,[1,3,a] Larry K. Pickering,[1] Walter A. Orenstein,[2,3] and Ram Yogev[4]

Departments of [1]Pediatrics and [2]Medicine, Emory University School of Medicine, and [3]Rollins School of Public Health, Emory University, Atlanta, Georgia, and [4]Department of Pediatrics, Northwestern University Feinberg School of Medicine, Chicago, Illinois

The direct impact of vaccines on children is well described, but the major public health impact of indirect protection provided to the community by vaccines is underappreciated. Community protection occurs when vaccinated persons block the chain of transmission, protecting undervaccinated or unvaccinated susceptible community members by preventing exposure and limiting the spread of the pathogen through the community. Substantial declines in disease incidence have occurred shortly after implementing new childhood vaccines, including declines among vaccine-ineligible children, adolescents, and adults. Protection of susceptible community members depends on maintaining high vaccination rates. Improved recognition of community protection will strengthen childhood vaccination strategies that will protect our communities into the future.

Keywords. indirect effect; herd; immunity; indirect; effect.

Child vaccination programs have reduced many infectious diseases to record-low incidences, with declines often exceeding the direct effect predicted from vaccine uptake and effectiveness. This additional decline beyond the direct effect of vaccination is referred to as *community protection,* which results from protection of "nonimmune" persons (eg, unvaccinated and not previously infected, vaccine failures) by reducing their risk of exposure to infection. Community protection has been referred to in the literature as *herd immunity, herd protection, herd effect, community immunity, indirect effect,* and *indirect protection*. We favor using "*community protection*" because the term does not imply that unvaccinated and other susceptible persons in the population are immune. Instead, susceptible persons and communities are protected from disease and death as vaccination breaks the chain of pathogen transmission in the community.

Vaccination has provided substantial community protection benefits to children and adults, with nearly all vaccine-preventable diseases showing ≥95% reductions in morbidity rates since vaccine introduction, despite vaccination rates that are much lower (Table 1) [1, 2]. Community protection is particularly important for persons who cannot receive vaccination (eg, those younger than the recommended age for vaccination, those with comorbid conditions, and those receiving chemotherapy) and for persons in whom an effective immune response does not develop after vaccination (eg, those with vaccine failure or primary or acquired immunodeficiencies). Community protection is vulnerable owing to politics, vaccine hesitancy, and clustering of unvaccinated and undervaccinated children. In this article, we review data supporting community protection among children and adults, discuss theoretical considerations, highlight limitations, and discuss strategies for optimizing community protection.

COMMUNITY PROTECTION OF UNVACCINATED CHILDREN AND ADULTS

Epidemiologic data have correlated marked declines in the burden of diseases with implementation of new vaccines recommended for children. These data exist across multiple pediatric vaccination platforms (Figure 1 and Table 1). Such data strongly suggest community protection, but they could reflect other secular trends (eg, changes in hygiene, other public health interventions). Community protection is particularly apparent when declines occur in the burden of disease observed in cohorts of children not eligible for vaccination and in unvaccinated adults. To demonstrate this, we highlight the impact of pediatric vaccination against 5 organisms: *Streptococcus pneumoniae*, rotavirus, *Haemophilus influenzae* type b (Hib), human papillomavirus (HPV), and rubella.

Rates of invasive pneumococcal disease (IPD) have declined in US children since introduction of heptavalent pneumococcal conjugate vaccine (PCV7) in 2000, with a 42% decrease in IPD rates noted in 2004 among infants <2 months old who were not targeted for PCV7 vaccination [13]. With introduction of 13-valent pneumococcal conjugate vaccine (PCV13) in 2010 (as a replacement for PCV7), the overall incidence of IPD declined

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[a]E. J. A. and M. A. D. contributed equally to this work.

Correspondence: E. J. Anderson, Emory University School of Medicine, 2015 Uppergate Dr, Atlanta, GA 30323 (evanderson@emory.edu).

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Table 1. Historical Comparisons of Morbidity for Select Vaccine-Preventable Diseases in the United States[a]

Vaccine-Preventable Disease	Mean Annual No. of Cases (Prevaccine Years)	2015 Vaccine Coverage, %[b]	Annual No. of Cases in 2016[c]	Prevaccine Annual No. vs Most Recent No. of Cases, % Reduction
Diphtheria	21 053 (1936–1945)	85	0	100
Hepatitis A	117 333 (1986–1995)	60	2500	98
Invasive Hib disease[d]	20 000 (1980s)	83	22	>99
Measles	530 217 (1953–1962)	92	69	>99
Mumps	162 344 (1963–1968)	92	5311	97
Pertussis	200 752 (1934–1943)	85	15 737	92
IPD, all ages	63 067 (1997–1999)	84	29 000	54
IPD, <5 y of age	16 069 (1997–1999)	84	1800	89
Polio, paralytic	16 316 (1951–1954)	94	0	100
Rubella	47 745 (1966–1968)	92	5	>99
Rotavirus[e]	62 500 (1990s)	73	11 250	82
Varicella	4 085 120 (1990–1994)	92	126 639	97

Abbreviations: Hib, *Haemophilus influenzae* serotype b; IPD, invasive pneumococcal disease.

[a]Data from Roush et al [1], Hill et al [2], and Sarah Roush, National Center for Immunization and Respiratory Diseases, Centers for Disease Control and Prevention (personal communication).

[b]Estimated vaccine coverage for ≥4 doses of diphtheria and tetanus toxoids and acellular pertussis vaccine; ≥2 doses of hepatitis A vaccine; ≥3 doses of Hib conjugate vaccine, depending on product received; ≥1 dose of measles-mumps-rubella vaccine; ≥4 doses of pneumococcal conjugate vaccine; ≥3 doses of inactivated poliovirus vaccine; ≥2 doses of rotavirus vaccine, depending on product received; and ≥1 dose of varicella vaccine.

[c]Annual number of cases for hepatitis A, IPD, rotavirus, and varicella in 2015.

[d]Cases estimated as invasive Hib disease among children <5 years old.

[e]Cases estimated as rotavirus hospitalizations among children <3 years old.

by 64% among children <5 years old and IPD caused by the 6 additional serotypes in PCV13 declined by 93% by 2013 when PCV13 coverage was 82%. Importantly, a 75% decline in incidence of PCV13-type IPD was observed among vaccine-ineligible children 5–17 years old [14].

Routine use of PCV7 in children <2 years old in the US significantly reduced IPD hospitalizations and in-hospital mortality rates in adults [14, 15]. Of the nearly 800 000 hospitalizations prevented from 2000 to 2006 by PCV7, 90% of the reduction in pneumococcal pneumonia occurred in adults [16]. A study in Connecticut found that zip codes with lower-than-average uptake of 3 or 4 doses of PCV7 had a higher prevalence of PCV7-type IPD cases in adults [17]. By 2012–2013, the 6 additional pneumococcal serotypes covered by PCV13 declined by 58%–72% in adult age groups, whereas non-PCV13 serotypes remained stable to slightly increasing [14]. Together, PCV7 and PCV13 have been estimated to have prevented nearly 400 000 cases of IPD (>50% decline in persons >5 years old) and about 30 000 deaths in the United States from 2001 to 2012 (nearly 90% decline in persons >5 years old) [14]. In addition, antibiotic-resistant IPD cases declined not only in children <5 years old (78% to 96%) but also in adults (50% to 69%) [14].

Routine infant rotavirus vaccination was implemented in 2006. By 2008 coverage with ≥1 dose had reached 57% in infants <1 year old and 17% in 1-year-olds but was negligible in children >2 years old [18]. Even so, national surveillance data showed significant reductions in both rotavirus-coded and cause-unspecified gastroenteritis hospital discharges among children of all ages in 2008, with further declines by 2010 [19]. Children <5 years old had experienced a 94% decline in rotavirus-coded hospitalizations by 2012, at which time vaccine coverage had reached only 69% among children 19–35 months old [20]. After implementation of infant rotavirus vaccination in 2006, declines in rotavirus diarrhea occurred in adults. Our data from Chicago demonstrated a 48% decline in the prevalence of rotavirus among adults who had diarrhea stool specimens submitted for testing after widespread pediatric rotavirus vaccination [21]. Similar declines were also noted in rotavirus-coded hospital discharges among older children and adults through age 44 years [19].

After implementation of Hib vaccination, a case-cohort study of the Navajo Nation (United States) children <2 years old living in communities in which 30% of children had received a dose of Hib vaccine had a 57% lower risk of invasive Hib than children in communities with 10% coverage [22]. National surveillance data from 1989 to 1991 show a 71% decline in Hib cases among US infants ≤14 months old, 1 year before vaccine was introduced for this age group [23]. Similar findings have been observed in Italy, the Gambia, and Israel [24–26].

The prevalence of genotypes covered by quadrivalent HPV (4vHPV) vaccine has declined by 64% among US girls and women 14–19 years old and by 34% among women 20–24 years old, compared with the prevaccine era [27]. These declines are greater than expected because only 51% of girls and women 14–19 years old and 33% of women 20–24 years old report receipt of ≥1 dose [27]. In the United States, 4vHPV serotypes were lower than nonvaccine HPV serotypes in boys and men 14–24 years old in 2013–2014. Although some impact was thought to be secondary to direct vaccination of young men, the difference was probably attributable primarily to community protection

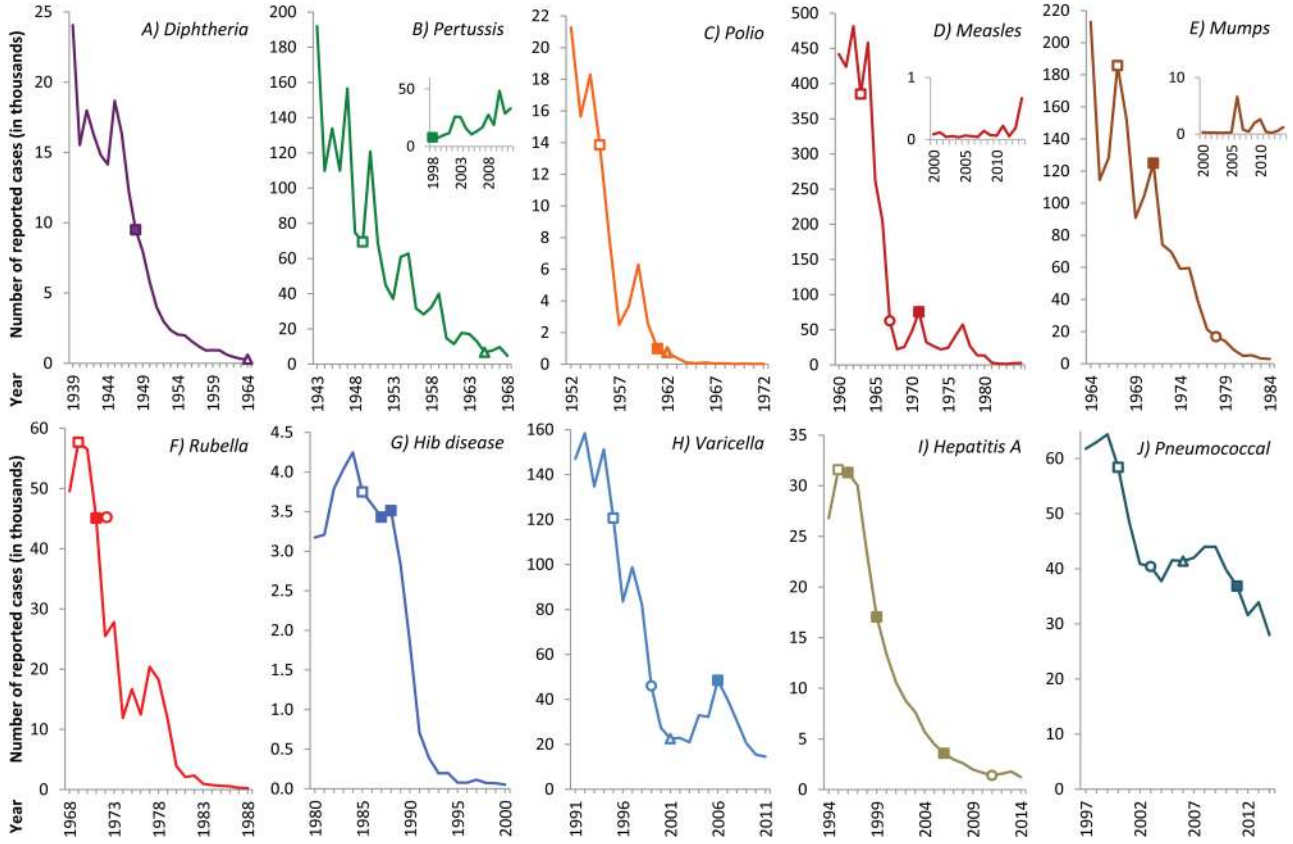

Figure 1. Annual reported cases of select vaccine-preventable diseases in the United States for 20–25-year periods, for diphtheria (*A*), pertussis (*B*), paralytic poliomyelitis (*C*), measles (*D*), mumps (*E*), rubella (*F*), *Haemophilus influenzae* type b (Hib) (*G*), varicella (*H*), hepatitis A (*I*), and invasive pneumococcal disease (IPD) (*J*); case numbers are estimated for Hib (including only children aged <5 years) and IPD. Open squares represent new vaccine introductions; filled squares, changes in vaccine or vaccination strategy; circles, 50% coverage reached for children aged 19–35 months; and triangles, 75% coverage reached for children aged 19–35 months or 1–4 years (depending on the survey). Data from the National Notifiable Diseases Surveillance System, Active Bacterial Core surveillance, Supplemental Pertussis Surveillance System, United States Immunization Survey, National Immunization Survey, and references [3–12]. Rotavirus, influenza, and adolescent vaccines (meningococcal serogroup C and human papillomavirus) were not included. Details for specific pathogens: *A,* Diphtheria toxoid was first licensed in 1923; diphtheria and tetanus toxoids and whole-cellular pertussis (DTwP) vaccine was introduced in 1948; coverage among children aged 1–4 years first reached 75% in 1964. *B,* Diphtheria and tetanus toxoids and acellular pertussis (DTaP) vaccine was first licensed in 1991; the US Advisory Committee on Immunization (ACIP) recommended DTaP vaccine for all 5 routine doses in 1998. *C,* Inactivated poliovirus vaccine was licensed in 1955 and oral poliovirus vaccine in 1961; coverage among children aged 1–4 years reached 75% in 1962. *D,* The first live virus measles vaccine was licensed in 1963; coverage among children aged 1–4 years reached 50% in 1967; measles-mumps-rubella (MMR) vaccine was licensed in 1971. *E,* Live, attenuated mumps vaccine was licensed in 1967; coverage among children aged 1–4 years reached 50% in 1978. *F,* Rubella virus vaccine was licensed in 1969; coverage among children aged 1–4 years reached 50% in 1971. *G,* Hib polysaccharide vaccine was licensed in 1985, and protein-conjugated Hib vaccine in 1987; a universal dose was recommended in 1988. *H,* Live varicella vaccine was licensed in 1995; coverage among children aged 19–35 months reached 50% in 1999 and 75% in 2001; a universal second dose was recommended in 2006. *I,* Hepatitis A vaccine was licensed in 1995 and was recommended for high-risk communities in 1996; the ACIP extended recommendations to include children living in states with high hepatitis A rates in 1999, universal vaccination was recommended to all newborns in 2006, and coverage among children aged 19–35 months reached 50% in 2011. *J,* Seven-valent pneumococcal conjugate vaccine was introduced for routine use in 2000, and coverage among children aged 19–35 months reached 50% in 2003 and 75% in 2007; 13-valent pneumococcal conjugate vaccine was introduced in 2010.

afforded by vaccination of girls and young women [28]. In unvaccinated Australian-born men ≤21 years old, the prevalence of 4vHPV genotypes decreased 31% after implementation of vaccination in girls and young women [29]. Furthermore, a study in Denmark noted a decline in genital warts from 365 to 77 per 100 000 person-years in unvaccinated young men, which correlated with HPV vaccination in young women [30].

Rubella vaccine was introduced to decrease the incidence of congenital rubella syndrome (CRS), which occurs when nonimmune pregnant women are infected with rubella virus early in pregnancy. In the United States a decision was made to vaccinate young boys and girls, the primary vectors of rubella transmission, and CRS rates rapidly declined [31]. In contrast, the United Kingdom and Japan targeted prepubertal girls for vaccination to provide direct protection as they entered childbearing years. Rubella infection and CRS unfortunately continued until routine vaccination of young boys and girls was implemented [32, 33].

THEORETICAL BASIS FOR COMMUNITY PROTECTION

To understand the basis for the community protection afforded by childhood vaccination observed among children and adults,

we present the theoretical background for this protection. Pathogen survival requires infection (or in some settings, colonization) of a susceptible person, who transmits the pathogen to other susceptible persons. In a totally susceptible population, the number of expected secondary cases from a single infected case is known as the basic reproduction number (R_0). The higher the R_0 the greater the number of expected cases and the greater the threshold of immune persons in the community needed to prevent an outbreak (Table 2). Some pathogens are highly transmissible (eg, measles R_0 = 12–18 cases and pertussis R_0 = 5–17 cases), whereas others have relatively low rates of transmission (eg, influenza R_0 = 1.4–4 cases) (Table 2) [10]. Because a population is rarely completely susceptible, the actual reproduction number (R_n) represents the number of observed secondary cases. R_n will vary considerably between populations because it depends on the biologic properties of the pathogen (eg, method of transmission and duration of shedding), host factors (eg, partial immunity and age), cyclic patterns of disease, and preexisting population immunity and heterogeneity. R_n will decrease as immunity in the population increases through vaccination or infection.

A threshold percentage of immune persons in the population is needed to eliminate transmission (generally conveyed as $[1 - (1/R_0)] \times 100$) (Figure 2) [10]. For example, if the R_0 for a given pathogen is 4, then the average infected person will infect 4 persons if the entire population is susceptible. If the immunity level of the population is <75%, pathogen transmission will be sustained and amplified. If the immunity level is >75%, then the average infected person will give rise to <1 new infection, and transmission will eventually stop. If 75% are immune, then only 1 new infection, on average, will occur, resulting in a constant level of transmission (the immunity threshold; Table 2). A high percentage of the population should be immune (approximately 92% or higher), or transmission of highly infectious pathogens such as measles and pertussis will be sustained. For less transmissible pathogens, including rubella and mumps, transmission can usually be halted by a lower percentage of population immunity (approximately 83% and 75%, respectively). These thresholds can vary based on age, social mixing patterns, and geography. It should be noted that the elegant theories of R_0, R_n, and threshold levels are extremely complex, and our understanding and ability to model community protection continue to evolve [10]. Nevertheless, the estimated threshold for elimination should provide a target for vaccination rates that would induce community protection.

Although achieving these threshold levels are crucial for eliminating disease, discussions of community protection frequently have neglected the data suggesting that vaccinating a smaller percentage of children can substantially reduce disease incidence. As demonstrated in Table 3, the mathematical impact of a vaccine can diminish the number of anticipated cases by >70% for a pathogen with an R_0 of 4–5 generations when only 25% of the population has been vaccinated. For example, the overall number of hepatitis A cases have declined 98% in the United States since vaccine introduction even though only 58% of children received ≥2 doses of hepatitis A vaccine in 2014 [11, 12]. Moreover, the annual US mortality rate for hepatitis A declined by 48% for persons 20–39 years old and by 37% in those ≥60 years old despite negligible rates of adult vaccination [34]. US surveillance data demonstrate declines in many vaccine-preventable diseases long before elimination thresholds are achieved (Figure 1).

Table 2. Approximate R_0 Values and Implied Thresholds for Eliminating Transmission of Common Vaccine-Preventable Diseases[a]

Infection	R_0	Crude Immunity Threshold for Eliminating Transmission, %
Diphtheria	6–7	83–85
Influenza[b]	1.4–4	30–75
Measles	12–18	92–94
Mumps	4–7	75–86
Pertussis	5–17	80–94
Polio[c]	2–20	50–95
Rubella	6–7	83–85
Smallpox	5–7	80–85
Varicella[d]	8–10?	?

Abbreviation: R_0, basic reproduction number.

[a]The values given in this table are approximate and do not properly reflect the tremendous range and diversity among populations. They also do not reflect the full immunologic complexity underlying the epidemiology and persistence of these infections. See text for further discussion. Implied thresholds were calculated as $1 - (1/R_0)$. (Table revised from Fine et al [10], with permission.)

[b]The R_0 of influenza viruses probably varies greatly between subtypes.

[c]Complicated by uncertainties over immunity to infection and variation related to hygiene standards.

[d]Immunity not sterile; crude immunity threshold not defined.

LIMITATIONS OF VACCINATION AND COMMUNITY PROTECTION

Community protection occurs only with vaccines that target pathogens that have humans as their only reservoir and not for pathogens that have a nonhuman reservoir (eg, tetanus, which has a soil reservoir). Community protection will require years to identify when a long latency exists between acute infection and its associated clinical outcome (eg, HPV vaccine against cervical and oropharyngeal cancers, hepatitis B vaccine against cirrhosis or liver cancer).

The term "immunity" often implies protection against both infection (pathogen replication in a host with or without symptoms) and disease (infection with associated symptoms). Reality is more complicated, as different vaccines induce variable protection against carriage, infection, disease, and contagiousness. For example, conjugate vaccines provide protection against carriage of Hib and *S. pneumoniae*, which affects transmission and results in greater community protection. Partial immunity may protect a vaccine recipient from severe disease manifestations (eg, rotavirus and hospitalizations) but may provide less protection against mild or asymptomatic infections [35]. Although

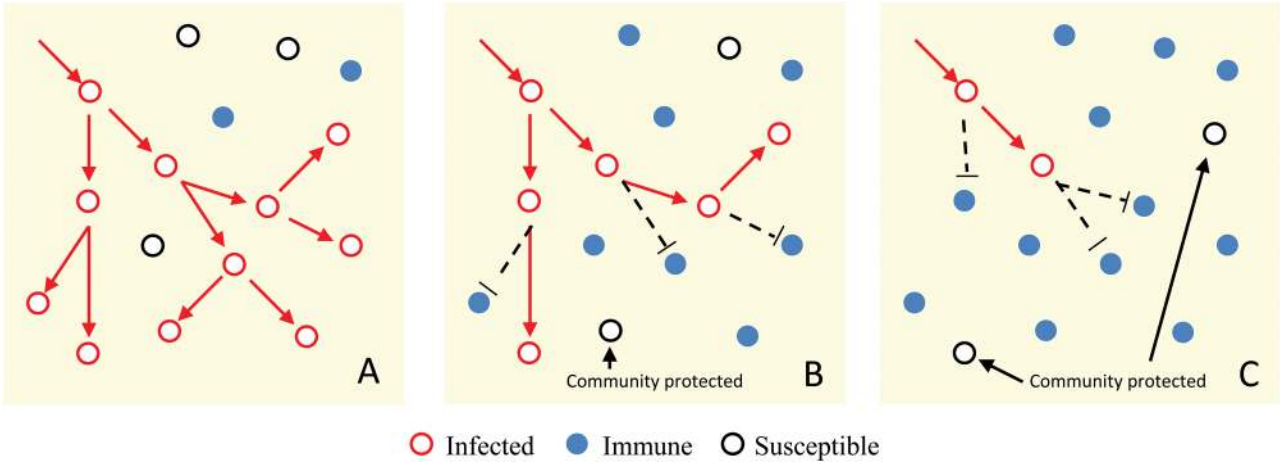

Figure 2. Transmission of a pathogen with a basic reproduction number of 2 in a population. *A,* If 12.5% of the population is immune, pathogen transmission increases exponentially for each generation (until previously infected individuals accumulate). *B,* If a 50% immunity level is achieved, transmission is impaired, and community protection can be observed. *C,* If 75% of the population is immune, transmission will be limited and will ultimately cease. Revised from Fine et al [10], with permission

most vaccines are highly effective, failure to respond immunologically to vaccination can occur. Additionally, the immunogenicity of a vaccine may vary with age [36], coexistent health conditions [37, 38], and concomitant medications [39].

Immunity can also wane as pathogen-specific immune responses decline without frequent "boosting" of the immune response by natural exposure or by vaccination. Waning immunity can weaken community protection and increase the risk of outbreaks (eg, resurgences of mumps among previously vaccinated university students) [40]. Thus, immunologically vulnerable persons rely on community protection, often without knowing it.

For some organisms, circulating strains may shift toward nonvaccine serotypes (eg, rotavirus G12P[8], *S. pneumoniae* serotype 19A after PCV7, and non-b *H. influenzae* [41]). Importantly, the net burden of disease has always declined after vaccine implementation, even when nonvaccine serotype rebound occurs [14, 21].

Although community protection has been observed for almost all pediatric vaccines (Figure 1 and Table 1), community protection has not been identified consistently with influenza vaccination. Monto et al [42] suggested that vaccination of school-aged children could limit household influenza transmission; they described the outcome of influenza vaccination in an intervention town with school vaccination (Tecumseh, Michigan) to a control town without school vaccination (Adrian, Michigan). After 86% of the schoolchildren were vaccinated, the rate of influenza-associated illnesses was 3 times lower in Tecumseh households. Data from Japan suggest that mandatory vaccination of school-aged children prevented 37 000–49 000 all-cause deaths per year, an effect that disappeared after discontinuation of mandatory vaccination for school-aged children [43]. Despite the potential for community protection, population-based data have not consistently supported this potential, presumably because circulating influenza strains frequently change and vaccination rates are relatively low.

It has been stated that vaccines are victims of their own success [44]. As vaccine-preventable diseases have become rare and their substantial morbidity and mortality rates forgotten (Figure 1 and Table 1), in part owing to community protection of the unvaccinated, complacency has grown, as have fears about potential vaccine side effects, resulting in vaccine

Table 3. Predicted Mathematical Expansion in the Number of Cases for a Pathogen with a Basic Reproduction Number of 4 and a Crude Immunity Threshold of 75%[a]

Proportion of Population With Immunity, %	Actual Reproduction Number	No. of Cases					
		1st Generation	2nd Generation	3rd Generation	4th Generation	5th Generation	Total Through 5 Generations
0	4	4	16	64	256	1024	1364
25	3	3	9	27	81	243	363
50	2	2	4	8	16	32	62
75	1	1	1	1	1	1	5
100	0	0	0	0	0	0	0

[a]Mathematical predictions based on an infinite population that is homogenous with complete mixing of cases among the remaining population. These assumptions will not be sustained in a real-world setting, particularly with increasing generations of disease.

hesitancy [44, 45]. Unvaccinated children are potentially spared the morbidity and mortality risks associated with vaccine-preventable diseases because of protection afforded by immunized children in the community. Community protection can generate a false sense of security; in part because vaccination rates can differ substantially within a population owing to nonrandom clustering.

For example, a retrospective study in Colorado evaluated the impact of personal exemptions on infections due to measles and pertussis. Vaccinated children (3–18 years old) residing in counties with a high frequency of exemptors to school immunization requirements had an increased risk of infection with measles (relative risk, 1.6; 95% confidence interval, 1.0–2.4) and pertussis (1.9; 1.7–2.1) compared with those in counties with low exemption rates [46]. Pertussis outbreaks also occurred more frequently among schools with higher rates of exemptors (mean, 4.3% vs 1.5%; $P = .001$) [46]. Census tracts in which exemptions are clustering are associated with a 2.5-fold increased odds of being in a pertussis cluster [47, 48]. Measles outbreaks, similar to the outbreak at Disneyland in 2014, have been linked to transmission of measles into largely unvaccinated communities [49].

MAXIMIZING COMMUNITY PROTECTION IN THE FUTURE

Direct protection of at-risk children through vaccination must remain the overall goal. This includes carefully evaluating expansion of vaccine recommendations to at risk populations [35]. If the enormous additional benefits to individuals and society from community protection are to be optimized, efforts are needed to achieve and maintain high vaccination rates. These include ensuring vaccine accessibility, continuing education about the benefits of vaccination, studying prevaccine epidemiology and the impact of vaccination, and including community protection in cost-effectiveness estimates.

Ensuring vaccines are accessible and administered to all children is crucial to maintaining the protection of our communities. The US Vaccines for Children program ensures that vaccines in the immunization schedule recommended by the Advisory Committee on Immunization Practices, Centers for Disease Control and Prevention, are covered without copay or deductible. Vaccines for Children has improved rates of vaccination, particularly in children living below the poverty line. Federal and state health systems should seek not just to remove financial barriers to vaccine access but also to ensure vaccine delivery and supply, promote public awareness of vaccine recommendations, and improve collaboration between state health departments and local providers [50].

Although difficult, research needs to better model and anticipate the future impact of community protection. Describing age-specific disease trends compared to vaccine coverage can be instrumental for informing national vaccine decisions. For example, surveillance data documenting residual breakthrough disease resulted in the US Advisory Committee on Immunization recommending booster doses of measles-mumps-rubella and varicella vaccines. Monitoring for replacement serotypes and modeling of pathogen transmissibility can help policy makers decide how to use current vaccines and if they should be reformulated (eg, replacement of PCV7 with PCV13). A cluster randomized study design can be used to assess the potential for community protection before vaccine licensure by randomizing clusters of individuals and compare attack rates among unvaccinated members of vaccinated clusters versus unvaccinated members of control clusters [51]. This method could be helpful in studies of new candidate vaccines.

It is important that healthcare-related savings attributable to community protection are included in economic evaluations of vaccination programs whenever possible. A study evaluating the US childhood vaccination program in 2009 found that $20 billion in direct costs were averted, but when indirect costs were included, such as time lost from work and travel by parents, the savings amounted to $76 billion [52]. In addition, vaccines affected the use of broad-spectrum antimicrobial agents [53] and antimicrobial resistance by reducing the circulation of multidrug-resistant bacterial pathogens [14]. Cost-effectiveness studies and mathematical models that appropriately account for community protection are crucial to inform policy; in some cases, the cost-effectiveness profile of a vaccine becomes favorable once community protection is recognized [54].

CONCLUSIONS

When receiving a vaccine, the recipient not only derives direct protection but also shields family, friends, and others from infection by blocking person-to-person spread of disease. Community protection is critical for nonimmune persons who rely on high levels of vaccine coverage for protection against infectious diseases. This includes infants too young to be vaccinated, pregnant women, the elderly, and persons with impaired immunity due to immune deficiencies (eg, cancer). The benefits of community protection provided by vaccination also provides an approach to addressing public health issues including antimicrobial resistance, pandemic influenza, Ebola virus, and Zika virus. The community protection provided by strong childhood and adult vaccination programs is crucial to maintaining and improving the health of all.

Notes

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References

1. Roush SW, Murphy TV; Vaccine-Preventable Disease Table Working Group. Historical comparisons of morbidity and mortality for vaccine-preventable diseases in the United States. JAMA **2007**; 298:2155–63.
2. Hill HA, Elam-Evans LD, Yankey D, Singleton JA, Dietz V. Vaccination coverage among children aged 19–35 months—United States, 2015. MMWR **2016**; 65:1065–71.
3. Adams DA, Fullerton K, Jajosky RA, et al. Summary of notifiable infectious diseases and conditions—United States, 2013. MMWR Morb Mortal Wkly Rep **2015**; 62:1–122.
4. Simpson DM, Ezzati-Rice TM, Zell ER. Forty years and four surveys: how does our measuring measure up? Am J Prev Med **2001**; 20:6–14.
5. National Immunization Survey (NIS)—children (19–35 months). Available at: https://www.cdc.gov/vaccines/imz-managers/coverage/nis/child/. Accessed 30 November 2016.
6. Adams DA, Thomas KR, Jajosky RA, et al. Summary of notifiable infectious diseases and conditions—United States, 2014. MMWR Morb Mortal Wkly Rep **2016**; 63:1–152.
7. Centers for Disease Control and Prevention. Summary of notifiable diseases in the United States. MMWR Morb Mortal Wkly Rep **1980**; 28:1–96.
8. Centers for Disease Control and Prevention. Summary of notifiable diseases, United States, 1993. MMWR Morb Mortal Wkly Rep **1994**; 42:1–73.
9. Adams DA, Jajosky RA, Ajani U, et al. Summary of notifiable diseases—United States, 2012. MMWR Morb Mortal Wkly Rep **2014**; 61:1–121.
10. Fine PEM, Mulholland K, Scott JA, Edmunds WJ. Community protection. In: Plotkin SA, Orenstein WA, Offit PA, Edwards KM, eds. Vaccines. Philadelphia, PA: Elsevier, **2018**:1512–31.
11. Centers for Disease Control and Prevention. Notice to readers: final 2013 reports of nationally notifiable infectious diseases. MMWR Morb Mortal Wkly Rep **2014**; 63:702.
12. Hill HA, Elam-Evans LD, Yankey D, Singleton JA, Kolasa M. National, state, and selected local area vaccination coverage among children aged 19–35 months—United States, 2014. MMWR Morb Mortal Wkly Rep **2015**; 64:889–96.
13. Poehling KA, Talbot TR, Griffin MR, et al. Invasive pneumococcal disease among infants before and after introduction of pneumococcal conjugate vaccine. JAMA **2006**; 295:1668–74.
14. Moore MR, Link-Gelles R, Schaffner W, et al. Effect of use of 13-valent pneumococcal conjugate vaccine in children on invasive pneumococcal disease in children and adults in the USA: analysis of multisite, population-based surveillance. Lancet Infect Dis **2015**; 15:301–9.
15. Whitney CG, Farley MM, Hadler J, et al; Active Bacterial Core Surveillance of the Emerging Infections Program Network. Decline in invasive pneumococcal disease after the introduction of protein-polysaccharide conjugate vaccine. N Engl J Med **2003**; 348:1737–46.
16. Simonsen L, Taylor RJ, Young-Xu Y, Haber M, May L, Klugman KP. Impact of pneumococcal conjugate vaccination of infants on pneumonia and influenza hospitalization and mortality in all age groups in the United States. MBio **2011**; 2:e00309–10.
17. Pingali SC, Warren JL, Mead AM, Sharova N, Petit S, Weinberger DM. Association between local pediatric vaccination rates and patterns of pneumococcal disease in adults. J Infect Dis **2016**; 213:509–15.
18. Cortese MM, Tate JE, Simonsen L, Edelman L, Parashar UD. Reduction in gastroenteritis in United States children and correlation with early rotavirus vaccine uptake from national medical claims databases. Pediatr Infect Dis J **2010**; 29:489–94.
19. Gastañaduy PA, Curns AT, Parashar UD, Lopman BA. Gastroenteritis hospitalizations in older children and adults in the United States before and after implementation of infant rotavirus vaccination. JAMA **2013**; 310:851–3.
20. Leshem E, Tate JE, Steiner CA, Curns AT, Lopman BA, Parashar UD. Acute gastroenteritis hospitalizations among US children following implementation of the rotavirus vaccine. JAMA **2015**; 313:2282–4.
21. Anderson EJ, Shippee DB, Weinrobe MH, et al. Indirect protection of adults from rotavirus by pediatric rotavirus vaccination. Clin Infect Dis **2013**; 56:755–60.
22. Moulton LH, Chung S, Croll J, Reid R, Weatherholtz RC, Santosham M. Estimation of the indirect effect of *Haemophilus influenzae* type b conjugate vaccine in an American Indian population. Int J Epidemiol **2000**; 29:753–6.
23. Adams WG, Deaver KA, Cochi SL, et al. Decline of childhood *Haemophilus influenzae* type b (Hib) disease in the Hib vaccine era. JAMA **1993**; 269:221–6.
24. Adegbola RA, Secka O, Lahai G, et al. Elimination of *Haemophilus influenzae* type b (Hib) disease from The Gambia after the introduction of routine immunisation with a Hib conjugate vaccine: a prospective study. Lancet **2005**; 366:144–50.
25. Dagan R, Fraser D, Roitman M, et al; Israeli Pediatric Bacteremia and Meningitis Group. Effectiveness of a nationwide infant immunization program against *Haemophilus influenzae* b. Vaccine **1999**; 17:134–41.
26. Gallo G, Ciofi degli Atti ML, Cerquetti M, Piovesan C, Tozzi AE, Salmaso S. Impact of a regional Hib vaccination programme in Italy. Vaccine **2002**; 20:993–5.
27. Markowitz LE, Liu G, Hariri S, Steinau M, Dunne EF, Unger ER. Prevalence of HPV after introduction of the vaccination program in the United States. Pediatrics **2016**; 137:e20151968.
28. Gargano JW, Unger ER, Liu G, et al. Prevalence of genital human papillomavirus in males, United States, 2013–2014. J Infect Dis **2017**; 215:1070–9.
29. Chow EP, Machalek DA, Tabrizi SN, et al. Quadrivalent vaccine-targeted human papillomavirus genotypes in heterosexual men after the Australian female human papillomavirus vaccination programme: a retrospective observational study. Lancet Infect Dis **2016**; 17:68–77.
30. Bollerup S, Baldur-Felskov B, Blomberg M, Baandrup L, Dehlendorff C, Kjaer SK. Significant reduction in the incidence of genital warts in young men 5 years into the Danish human papillomavirus vaccination program for girls and women. Sex Transm Dis **2016**; 43:238–42.
31. Williams NM, Preblud SR. Rubella and congenital rubella surveillance, 1983. MMWR CDC Surveill Summ **1984**; 33:1SS–10SS.
32. Anderson RM, Grenfell BT. Quantitative investigations of different vaccination policies for the control of congenital rubella syndrome (CRS) in the United Kingdom. J Hyg (Lond) **1986**; 96:305–33.
33. Nationwide rubella epidemic—Japan, 2013. MMWR Morb Mortal Wkly Rep **2013**; 62:457–62.
34. Vogt TM, Wise ME, Bell BP, Finelli L. Declining hepatitis A mortality in the United States during the era of hepatitis A vaccination. J Infect Dis **2008**; 197:1282–8.
35. Anderson EJ. Time to begin a new chapter and expand rotavirus immunization. Clin Infect Dis **2014**; 59:982–6.
36. Mulligan MJ, Bernstein DI, Winokur P, et al; DMID 13-0032 H7N9 Vaccine Study Group. Serological responses to an avian influenza A/H7N9 vaccine mixed at the point-of-use with MF59 adjuvant: a randomized clinical trial. JAMA **2014**; 312:1409–19.
37. Nath KD, Burel JG, Shankar V, et al. Clinical factors associated with the humoral immune response to influenza vaccination in chronic obstructive pulmonary disease. Int J Chron Obstruct Pulmon Dis **2014**; 9:51–6.
38. Brydak LB, Machała M, Centkowski P, Warzocha K, Biliński P. Humoral response to hemagglutinin components of influenza vaccine in patients with non-Hodgkin malignant lymphoma. Vaccine **2006**; 24:6620–3.
39. Yri OE, Torfoss D, Hungnes O, et al. Rituximab blocks protective serologic response to influenza A (H1N1) 2009 vaccination in lymphoma patients during or within 6 months after treatment. Blood **2011**; 118:6769–71.
40. Patel LN, Arciuolo RJ, Fu J, et al. Mumps outbreak among a highly vaccinated university community—New York City, January–April 2014. Clin Infect Dis **2017**; 64:408–12.
41. MacNeil JR, Cohn AC, Farley M, et al. Current epidemiology and trends in invasive *Haemophilus influenzae* disease—United States, 1989–2008. Clin Infect Dis **2011**; 53:1230–6.
42. Monto AS, Davenport FM, Napier JA, Francis T Jr. Modification of an outbreak of influenza in Tecumseh, Michigan by vaccination of schoolchildren. J Infect Dis **1970**; 122:16–25.
43. Reichert TA, Sugaya N, Fedson DS, Glezen WP, Simonsen L, Tashiro M. The Japanese experience with vaccinating schoolchildren against influenza. N Engl J Med **2001**; 344:889–96.
44. Orenstein WA, Ahmed R. Simply put: vaccination saves lives. Proc Natl Acad Sci USA **2017**; 114:4031–3.
45. Edwards KM. State mandates and childhood immunization. JAMA **2000**; 284:3171–3.
46. Feikin DR, Lezotte DC, Hamman RF, Salmon DA, Chen RT, Hoffman RE. Individual and community risks of measles and pertussis associated with personal exemptions to immunization. JAMA **2000**; 284:3145–50.
47. Omer SB, Enger KS, Moulton LH, Halsey NA, Stokley S, Salmon DA. Geographic clustering of nonmedical exemptions to school immunization requirements and associations with geographic clustering of pertussis. Am J Epidemiol **2008**; 168:1389–96.
48. Atwell JE, Van Otterloo J, Zipprich J, et al. Nonmedical vaccine exemptions and pertussis in California, 2010. Pediatrics **2013**; 132:624–30.
49. Halsey NA, Salmon DA. Measles at Disneyland, a problem for all ages. Ann Intern Med **2015**; 162:655–6.

50. Protecting the public's health: critical functions of the Section 317 Immunization Program—a report of the National Vaccine Advisory Committee. Public Health Rep **2013**; 128:78–95.
51. Clemens J, Shin S, Ali M. New approaches to the assessment of vaccine herd protection in clinical trials. Lancet Infect Dis **2011**; 11:482–7.
52. Zhou F, Shefer A, Wenger J, et al. Economic evaluation of the routine childhood immunization program in the United States, 2009. Pediatrics **2014**; 133:557–85.
53. National Vaccine Advisory Committee. A call for greater consideration for the role of vaccines in national strategies to combat antibiotic-resistant bacteria: recommendations from the National Vaccine Advisory Committee—approved by the National Vaccine Advisory Committee on June 10, 2015. Public Health Rep **2016**; 131:11–6.
54. Dhankhar P, Nwankwo C, Pillsbury M, et al. Public health impact and cost-effectiveness of hepatitis a vaccination in the United States: a disease transmission dynamic modeling approach. Value Health **2015**; 18:358–67.